ERRATUM - On Page 785, Column 2, Lines 15 and 16 make reference to "Figure 1, lower". It should correctly read "Figure 1, upper".

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Structures to Prevent the Spread of Nuisance Fish from Lake Davis, California

DOUGLAS B. C. RISCHBIETER*

California Department of Water Resources, Division of Planning and Local Assistance, Northern District, 2440 Main Street, Red Bluff, California 96080-2356, USA

Abstract.—Methods to contain the spread of nuisance or otherwise undesirable fish species are relatively limited. I describe an unconventional method used to help restrict the movement of northern pike *Esox lucius* from a mountain reservoir into downstream waters. Reservoir managers designed, installed, and monitored steel structures ("graters") that served to increase the likelihood that fish entrained in discharge from Lake Davis (Plumas County, California) would incur fatal trauma. Seven species of fish, cumulatively hundreds of individuals, were observed killed by the graters. Injuries induced included dismemberment, lacerations, abrasions, and contusions. No failures to induce fatal trauma to entrained fish were observed, though a few crayfish *Pacifasticus* spp. remained alive after only partial dismemberment. The graters were fabricated from commercially available steel and sized to fit over 10-in and 30-in discharge ports of the outlet works. Reservoir and fishery managers could adapt these designs for use at a variety of other outlet facilities where interim measures are desired to contain the spread of nuisance fish.

The wealth of research compiled on the subject of reducing mortality of fish entrained at dams and diversions (EPRI 1992) is not conversely applicable when the opposite result is desired. At Grizzly Valley Dam (Lake Davis, Plumas County, California), our ideal objective was 100% mortality of northern pike *Esox lucius,* an isolated occurrence of an illegally introduced species, to prevent colonization of downstream waters. Even the most complex series of penstocks and turbines do not cause trauma to every passing fish (Bell and DeLacy 1972). Attempts to screen or reduce entrainment using temporary barriers are also typically less than 100% efficient, require substantial cleaning and maintenance (Stober et al. 1983), or are prone to episodic failure.

In December 1996, at the request of the California Department of Fish and Game (CDFG), the California Department of Water Resources (CDWR) designed and installed two unique structures at the outlet valves of Grizzly Valley Dam. These structures, termed "graters," were conceived to increase the likelihood that northern pike passing through the outlet works would suffer fatal trauma. Incidental mortality of desirable fish species was of minimal concern. Because there is no published record of such measures being used to prevent the spread of invasive nuisance fish species from a reservoir into downstream areas, CDWR conducted monitoring to determine the effectiveness of these structures. Documentation of those methods and monitoring observations may be useful to other reservoir and fishery managers.

Study Site

Lake Davis is on Big Grizzly Creek in the headwaters of the Feather River (tributary to the Sacramento River and thence the Sacramento–San Joaquin Delta). Created in 1967 by Grizzly Valley Dam, Lake Davis is about 6 miles north of Portola, California. At about 4,026 surface acres, when full to its spillway elevation of 5,775 ft above sea level, it has 84,370 acre-feet of storage. The mountainous drainage area covers about 44 mi^2. Water stored in Lake Davis provides recreation and fish and wildlife enhancement, streamflow enhancement, and domestic and agricultural water supply.

Surface water can flow from Lake Davis via three direct routes. When reservoir surface elevation exceeds 5,775 ft, water passes over the ungated spillway. Since the discovery of northern pike in the reservoir, CDWR has operated Grizzly Valley Dam to avoid spill. Most of the time, releases are controlled by outlet works that include (1) an intake structure that draws water from one or more of three discrete reservoir levels, and (2) an outlet control structure that can release water through either or both 10-in and 30-in butterfly valves. When the outlet works are temporarily shut down for maintenance, a 10-in siphon (which is permanently installed over the spillway) is activated and delivers about 3 or 4 ft^3/s to maintain flow in the creek.

Water discharged through the butterfly valves normally strikes a concrete energy dissipater (per-

* E-mail: dougr@water.ca.gov

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pendicular suspended wall) that is part of an 18 × 24-ft stilling basin. The velocity of discharged water has been calculated to be between 40 and 80 ft/s at the outlet ports, and the pressure is about 50 lb/in^2 (CDWR 1992). Outlet works of this type have been documented to cause substantial mortality, but fish can also occasionally survive the impact of the energy dissipater (CDWR 1996). A measuring weir spans the creek about 50 ft downstream from the stilling basin.

Methods

Construction and installation.—Engineers, in fabricating the graters, chose materials that were readily available and expected to withstand the forces of varying volumes of high-velocity water contact. Individual components are pieces of commercially available hot-rolled flat steel, steel rounds, steel angles, and square tubing ranging from 3/16 in to 5/8 in thick. Pieces were generally welded together but a few were bolted. As-built construction detail drawings can be obtained from the author.

Each grater is of differing design, although they operate in fundamentally the same manner. The grate mesh was selected to presumably cause more severe injuries to entrained fish than would contact with a flat surface, such as a plate or the concrete wall; however, the mesh allows water to pass with a limited, acceptable increase in impedance. Design differences required differences in installation. When fully assembled, the large grater was too heavy for manual attachment and therefore was assembled in modules. The small grater was completely preassembled and installed easily as a single unit. The graters were installed on December 13, 1996. For installation, flow through the outlet structure was shut off and the stilling basin was dewatered. Streamflow was maintained by activating the siphon for a day.

Both graters are mounted so that all water discharged from their respective port contacts or passes through them (no bypass). The large grater in situ (installed in front of the 30-in discharge port) is shown in Figure 1. The finished structure is approximately 56 in tall by 52 in wide, extends about 2 ft away from the concrete face of the outlet control house and discharge port, and weighs about 980 lb. It is situated with the bottom about 3 ft above the bottom of the stilling basin (thus, the bottom of this grater is normally slightly submerged) and with the 30-in discharge port centered horizontally. The mesh openings of the grate are two different sizes: 1.1-in squares (inside 1.5-in-square tubes) and about 1.5 × 3.0 in (spacing between welded members).

The small grater is installed in front of the 10-in discharge port (Figure 1, upper). It is approximately 21.5 in square, extends about 21.5 in away from the concrete face of the outlet control house and discharge port, and weighs about 175 lb. Initially and during monitoring, the small grate module had only three 3/8-in rounds (vertical members), thus the width of the grate spaces was relatively large. An additional three rounds were installed after it was noted that the large grater, with its smaller grating apertures, induced greater trauma to entrained fish. During monitoring the grate mesh was approximately 1.6 × 3.7 in (Figure 1, lower); it is now about 1.6 in × 1.8 in.

Monitoring.—Monitoring techniques available to analyze long-term fish entrainment in high-pressure valve discharge are limited. Our effort began after it became obvious that dismembered fish were accumulating on the bottom, banks, and submerged vegetation of Big Grizzly Creek and were also being dispersed downstream. In general, only qualitative assessment was feasible during and immediately after use of the 30-in valve (meaningful observation during valve operation was especially limited). We used a quantitative method for measuring fish discharge through the 10-in valve.

The 30-in valve was in operation from December 13, 1996, to May 16, 1997, from September 23 through October 13, 1997, from March 4 through May 25, 1999, and from August 25 through September 21, 1999. Because of the constraints discussed later, only cursory evaluation of the fish killed by the large grater during these periods was possible. During brief periods when the large valve was occasionally temporarily shut off, we snorkeled in the stilling basin, inspected the integrity of the graters, and walked and snorkeled the stream channel for about 200 ft downstream. This allowed us to remove and identify dead fish and fish parts and otherwise evaluate grater operation. We took advantage of such opportunities on seven occasions: December 20, 1996; March 8, April 16, May 22, and October 14, 1997 (all before chemical treatment of the reservoir); and April 23 and September 23, 1999 (both after the reservoir had been restocked with about 1,000,000 rainbow trout *Oncorhynchus mykiss*). Water temperature was also measured on each date.

The small valve was often closed when the large valve was in use, except when maximum discharge was required (usually to avoid spill). Both valves were fully open from December 29, 1996, to Feb-

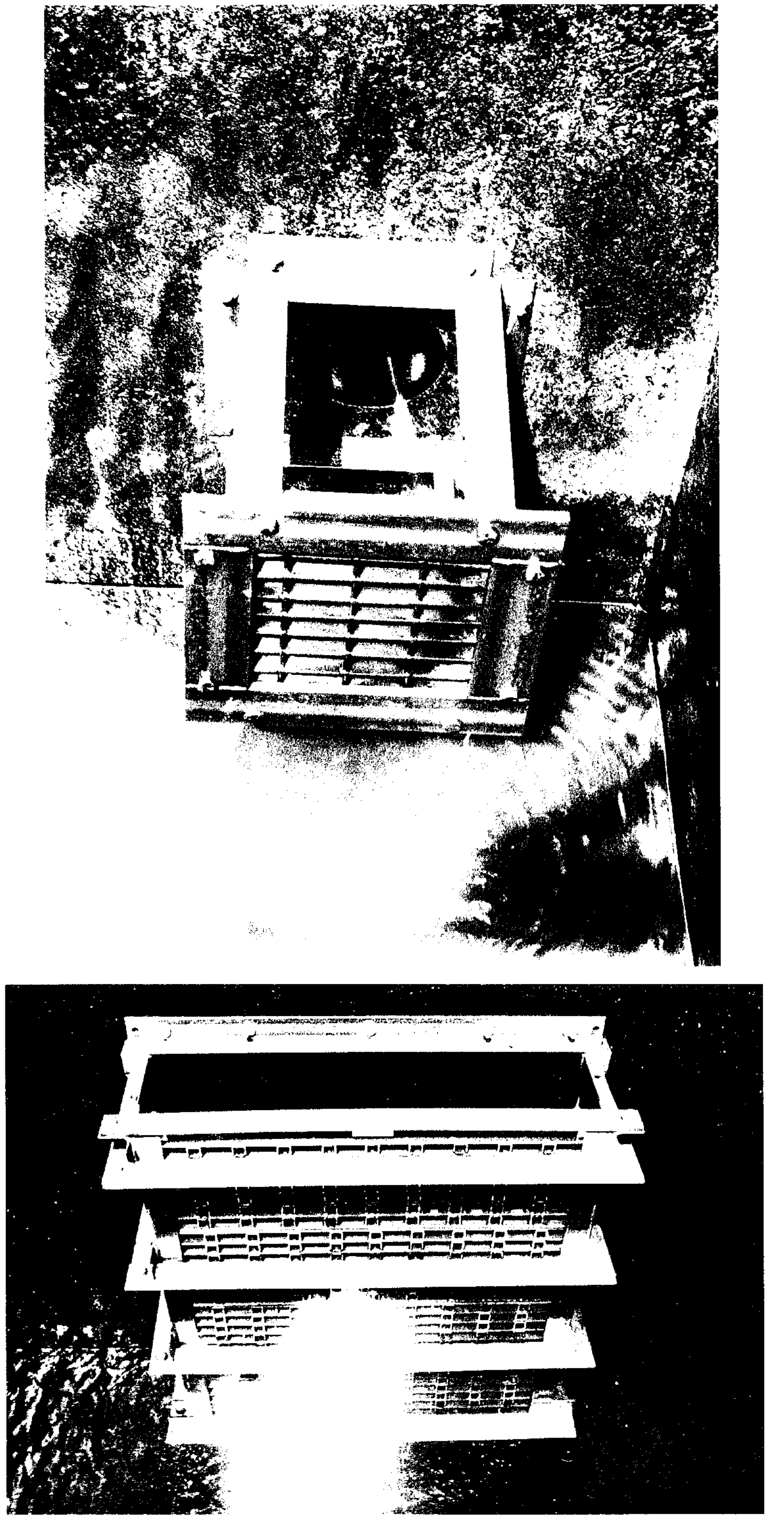

FIGURE 1.—Oblique views from above of the large grater (lower), installed in front of 30-in discharge port (photo also shows water spray from valve leakage), and small grater (upper), installed in front of 10-in discharge port, at Grizzly Valley Dam, California, in 1996.

ruary 27, 1997, and all three intake gates were also open. When the large valve was closed, the small valve was normally set to discharge 10 ft^3/s. The small valve and grater were in sole use from May 17 through September 22, 1997, and October 14, 1997, through March 18, 1998. The unit was temporarily removed on March 19, 1998, for modification of the mesh size. The refitted unit was reinstalled on May 21, 1998, for a few weeks, removed for a year thereafter (after the chemical eradication project had appeared to be successful), and reinstalled in May 1999 when additional northern pike were discovered.

The small grater could not be evaluated during high flows (both valves open). However, during releases of 10 ft^3/s we could safely enter and snorkel in the stilling basin and the creek with sufficient visibility to count all fish. We did this twice daily from May 27 (evening) through June 4 (morning), 1997. To measure the rate at which fish and fish parts were discharged in this release (10 ft^3/s), we isolated the stilling basin by securing a net (0.25-in mesh) across the creek at the outlet sill of the stilling basin on May 27. The net was secured with ropes and extended about 3 ft above the water surface; it was secured along its bottom (on top of the sill) by placement of concrete blocks along the sill.

We emptied resident fish from the stilling basin enclosure over a 3-d period (May 27–29) by a combination of electrofishing, netting, and herding. These fish (all rainbow trout) were given an adipose fin clip and released about 200 ft downstream. Twice each day, around dawn and dusk, from May 28 until June 3 we methodically searched both the net and the stilling basin (by snorkeling) for newly deposited fish parts or carcasses and removed any found. Organisms and carcasses collected were identified to species and measured to the nearest 0.5 in. Water temperature was measured several times during the latter half of the small-grater sampling period.

Results

Fish Passage and Mortality

Fish parts were readily evident in the vicinity of the graters within days of their installation. Of the seven dates of large-grater monitoring (when closer scrutiny and removal of fish parts was undertaken), dead and dismembered fish were widely scattered in all instances except May 22, 1997, and April 23, 1999. Fish parts and carcasses that did not float over the sill of the stilling basin accumulated in the corners of the basin (submerged). Injuries observed included dismemberment, lacerations, abrasions, and contusions. Because many fish had been dismembered into small parts, it was difficult to quantify the number (or original size) of individual carcasses in the sampling area. Typical estimates during these and other observations at the site ranged from less than 10 to 30–40 individuals of various sizes per occasion. Pieces were observed in various states of decay, indicating they had been dead for different lengths of time. It was also obvious that many, probably most, pieces had been swept and distributed downstream where they were not readily retrievable. Animal footprints on the streambanks also suggested that scavengers may have removed some carcasses. On all dates, live rainbow trout were present in nearby stream pools but not in the stilling basin.

The following species of dead fish were observed (listed in order of apparent abundance): brown bullhead *Ameiurus nebulosus,* northern pike, rainbow trout, redear sunfish *Lepomis microlophus,* golden shiner *Notemigonus crysoleucas,* black basses *Micropterus* spp., and bluegill *L. macrochirus.* Additionally, abundant dismembered crayfish *Pacifasticus* spp. and the head of one common merganser *Mergus merganser* were also collected.

After we placed the net to monitor the small grater, we removed all but three rainbow trout from the stilling basin (fish apparently from Big Grizzly Creek that had migrated upstream and evaded capture efforts). We then collected 19 brown bullheads (whole or in pieces; all dead in the net or basin) and 2 bluegills between May 28 and June 4. These were invariably small individuals; the brown bullheads ranged from 2 to 10 in, and the bluegills were both 1.5 in (age 0). No live fish of any species appeared in the stilling basin or net during the sampling period. Several dozen crayfish of various sizes also passed through the valve during the sampling period. Three were collected alive (each about 2 in total length): one whole, one with one claw, and one that had lost both claws.

No eggs or northern pike were collected or observed during small-grater sampling, nor was there a substantial amount of other matter (plants, detritus, etc.) in the discharge of 10 ft^3/s. The temperature of the discharged water was approximately 57°F on all May and June sampling dates, between 50°F and 60°F on September and October dates, and between 40°F and 50°F on December through April dates.

Structural Performance

On April 16, 1997, we noticed that two of the four outer-face members of the large grater had broken. This structural failure may have been due to water impact and cavitation or to the impact of numerous pieces of copper tubing that were entrained in the discharge on one occasion. In any case, these broken members did not compromise the effectiveness of the grater, but all four were replaced and strengthened to ensure structural integrity. Subsequently, through the last use on September 21, 1999, the grater functioned without problem nor evidence of wear or degeneration.

No structural failure or physical performance problems were associated with the small grater. As described earlier, three additional vertical members were installed, after monitoring, to constrict mesh size. The initial larger apertures, combined with less grate surface area and the lesser bluntness of the round steel components (compared with large grate design), seemed to induce less trauma to fish. No wear or degeneration was observed, though the bolts attaching the smaller grater to the mounting surface occasionally needed tightening. No entrained matter was observed clogging or cluttering either grater.

Discussion

The graters appeared to ensure that fish entrained in Grizzly Valley Dam discharge were killed and did not have an opportunity to become established downstream in Big Grizzly Creek. The graters required little maintenance, owing in part to strong construction materials and also because the water velocity and pressure was sufficient to prevent matter from accumulating on them.

The graters typically induced a great deal of trauma to individual fish. Smaller individuals appeared more likely to avoid dismemberment, by passing through the mesh, but were probably killed by impacting the concrete energy dissipater. Presumably, the large grater is more effective because it has more surface area in the discharge stream than the small grater. Occurrences of apparently minor injuries, such as abrasions, which might indicate only a glancing impact had occurred, were always fatal in fish we observed. However, the survival of three small crayfish illustrate that the graters have some limitations. A grater would not be expected to be effective in controlling movement of eggs or larval fishes. Conversely, larger organisms are less likely to avoid physical contact with the grater. Stier and Kynard (1986) noted that larger fish are more likely than small fish to suffer mortality when passed through valves and other mechanical features. Operational changes (such as selective intake use, if available) can to some degree selectively reduce the frequency of small fish entrainment and thus increase the overall mortality rate.

Operational details also probably influence differences in entrainment rates among species. The relative abundance of brown bullheads and crayfish was probably due to their relative abundance in the lake and the fact that the lowest (near bottom) intake gate was slightly open (due to hydraulic failure). Bullheads are typically benthic (Moyle 1976) and could more readily enter the outlet works through the lowest intake gate. Middle and upper intake gates are more oriented to draw water from the pelagic zone of the reservoir. Volume of discharge also may affect entrainment rates and partially explain why only two species of fish were observed passing through the 10-in valve, whereas at least seven species were collected from the large valve. Discharge volume may also be part of the reason that only relatively small individuals were collected while the 10-in valve was in use (i.e., larger fish may be more likely to avoid entrainment through stronger swimming ability).

By avoiding use of the near-surface intake gate, CDWR probably minimized the possibility that early life stages of northern pike would be entrained in the outflow. The period when the sampling net was in place coincided with northern pike spawning and hatching season, and some of their eggs or larvae would probably adhere to the net had they been present in moderate abundance. Northern pike present in the hypolimnetic zone during spring, when the large Grizzly Valley Dam valve is often open to avoid spill, are likely to be substantially larger than the juvenile brown bullheads and bluegills killed by the small grater and therefore less likely to survive passage through the valve and associated encounter with the grater and energy-dissipation structure.

Dismembered rainbow trout below the grater were absent on the April 23, 1999, inspection and in several cursory inspections during the weeks preceding large-valve use. This might be considered surprising because Lake Davis had been stocked with about 1,000,000 rainbow trout since July 1998. The absence of dismembered trout indicates that few trout are typically present near the middle intake gate during late winter and early spring, perhaps because of diminished rainbow trout activity at temperatures below their optimum range (Moyle 1976). The absence of fish parts on May 22, 1997, is noteworthy for another reason. This inspection, 1 week after flows had been lowered from 90 to 10 ft^3/s, followed a period when fish parts had been common. It is likely that animals were better able to scavenge the streambed at lowered flows. This underscores the importance of timing such qualitative monitoring immediately after flow reduction.

The future holds opportunities to further describe both grater efficiency and fish entrainment through regulated discharge. For CDWR, the graters were intended as a temporary measure, to be removed when the threat posed by northern pike in Lake Davis had passed. Monitoring conducted by CDWR was secondary to the primary purpose of successfully completing CDFG's eradication project, so operational latitude to allow monitoring of the graters over a wider range of conditions (flows, varying use of intake gates, longer duration, introduction of marked fish at intake, etc.) was not possible. However, some observations may help future investigators overcome some difficulties. For example, it appeared that the high flows occurring during operation of the 30-in valve would not allow secure, long-term placement of sampling nets at the stilling basin. Collection of fish parts from the stilling basin was also not possible because of the turbulence during these flows. Dead fish and fish parts initially appeared to be too numerous for effective use of a fyke net or similar gear (mesh on net would quickly clog and potentially fail). Besides the technical hurdles to overcome, a more detailed study would also be substantially more costly and labor intensive.

Water managers should be aware that presence of the graters diminished the capacity of the discharge valves. Whereas the 30-in valve had historically discharged a maximum of about 235 ft^3/s when fully open, only about 200 ft^3/s could be discharged after the large grater was installed. This loss of efficiency (about 15%) was also typical of other smaller-aperture settings of the valve (R. Howell, CDWR, personal communication). This effect should be considered by future users of such devices if modification of the mesh design is contemplated (e.g., if smaller spaces between the square tubes are desired). The large-grate design described herein occludes more than 30% of the area of the discharge port. Modifying the distance that the grates are installed from the discharge port will also influence the capacity of the valve: less flow reduction if the grate modules are positioned further from the discharge port, more flow reduction if closer. Thus, optimum design of any future application will also have to include consideration of the forces and stresses to be withstood on a case-by-case basis.

Managers contemplating use of such devices should also consider public perceptions of the results. Dead fish are readily observed by anglers and other streamside visitors. Media reports about the Lake Davis graters frequently included errors and misunderstandings of their function. Because these devices can kill desirable fish and wildlife in addition to nuisance fish, information about resource costs and benefits should be made readily available.

The threat of an expanding northern pike distribution in California continues. The graters are an important factor complementing other management efforts to contain and eradicate this species. Results of grater monitoring, and other operational measures implemented at Lake Davis, suggest that northern pike from Lake Davis have probably not escaped into downstream waters. In fish population studies in Big Grizzly Creek in recent years, CDFG and CDWR have collected no northern pike or other fish of obvious Lake Davis origin (CDWR, unpublished data). Significant spill from Lake Davis has been avoided since 1986; the few-hundredths of a foot of water that rose above the spillway in 1995 and 1996 for a short duration was unlikely to allow fish emigration via that route (CDWR 1996, 1998). Sporadic anecdotal reports of northern pike downstream from Lake Davis (Lake Oroville, March 1998; Middle Fork Feather River, summer 1996 and 1997; CDWR Banks Pumping Plant [southern Sacramento–San Joaquin Delta], winter 1996–1997) are not surprising, however. Northern pike were first confirmed in Lake Davis in 1994 (CDFG 1997); high-volume discharge from Grizzly Valley Dam occurred for four full months in 1995 and 102 d in 1996, which preceded installation of the graters. The siphon was also used on two occasions, during one occasion a 16-in northern pike was caught after moving through it. However, it is encouraging that these occurrences to date appear to have been isolated, solitary individuals and no evidence of another northern pike population or reproduction has been found.

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